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ANGULAR MOMENTUM AND THE AIRCRAFT-STORE SEPARATION PROBLEM

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FOREWORD

This report describes work directed toward alleviating the aircraft-store separation problem.

Acknowledgement is due to C. J. Cohen, Research Associate for the Warfare Analysis Department. Equation 2 is due to him.

This work was performed under the Independent Exploratory Development Program sponsored by the Director of Naval Laboratories.

This report was reviewed by R. D. Cuddy, Head of the Aeroballistics Division.

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ABSTRACT

The stability criterion of a missile containing an internal spinning fly wheel is derived and the effect of this fly wheel on the missile's launch disturbance is explained.

CONTENTS

I INTRODUCTION

Aircraft-store separation is a serious consideration for both weapon and aircraft designers. The weapon designer wants to avoid the large release disturbance since it affects the weapons accuracy. The aircraft designer wants to avoid the large release disturbance since it is dangerous to the pilot and can result in damage to the aircraft.

There have been various methods of improving weapon separation characteristics but none has been entirely satisfactory since they are based largely upon trial and error. Present systems are rather erratic in their separation characteristics due to variation in store configurations.

In retrospect, it is quite unlikely that a store separation problem existed when aircraft flew at 250 knots and dropped 2000 lb. bombs due to the inertia loads being much greater than the aerodynamic loads. The bombs were aerodynamically inert at release.

However, aircraft speed has increased considerably. The aerodynamic loads increased with velocity squared and store separation became a problem. Weapon accuracy was reduced and aircraft damage was sustained.

Aircraft can now carry high density, externally stored weapons supersonically. It would also be advantageous to launch these weapons supersonically. The aerodynamic loads will be much larger and if large release disturbances are encountered, the damage to the aircraft can be severe.

One method of alleviating the store separation problem is to gyroscopically increase the weapon's inertial forces by inserting a spinning fly wheel. Admittedly, this is an added complication but it may be required to solve the problem. It is the purpose of this paper to present the mechanics of the internally stabilized weapon.

II. RIG[illegible] BODY DYNAMICS

From the linear theory of missile dynamics it can be shown that an approximate solution for the angle of attack of a spinning, symmetric, rigid body (neglecting damping) is

$$\vec{\alpha} = K_1 \; e^{i\omega_1 t} + K_2 \; e^{i\omega_2 t} \qquad (1)$$

If [illegible] at $t = C$ then it may be shown that for an initial angular rate the [illegible] angle of attack is

$$|\vec{\alpha}_{MAX}| = 2 \, |\dot{\vec{\alpha}}_0| / \sqrt{(p^2 I_x^2/I_y^2) - 4M_\alpha/I_y} \qquad (2)$$

Consequently, for statically stable configurations, the maximum angle of attack due to an angular rate may be reduced by increasing the angular momentum or by increasing the restoring moment. It is suggested that external stores be designed in accordance with equation 2.

The restoring moment for an external store is usually small due to the design conforming to space limitations. However its angular momentum may be increased considerably.

Two methods of increasing the angular momentum of external stores are readily apparent. The first would require spinning the store on the rack. This method would necessitate a complicated rack design which would probably not work for all stores. Moreover, the stores would be released with a high spin rate and be subject to Magnus instability.

A second method for increasing the angular momentum of an external store is to spin an internally mounted fly wheel. This method would work equally well for all types of racks. It is interesting to note that a store with an internally spinning fly wheel, if dropped in the free fall mode, would not spin appreciably because the store and fly wheel fall at the same rate. Consequently, the torque due to friction coupling could not act efficiently. It is conceivable that the spin of the store could be optimized for stability by using fin cant or roll tabs.

Frick[1] of the Naval Weapons Laboratory has derived the equations for motion for two rigid bodies coupled by a bearing. In a body fixed reference frame (rolling with the outer body) the six-degree-of-freedom equations are:

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ w \end{bmatrix} = (1/m) \begin{bmatrix} F_{x_B} \\ F_{y_B} \\ F_{z_B} \end{bmatrix} + \begin{bmatrix} rv - qw \\ p_1 w - ru \\ qu - p_1 v \end{bmatrix} \tag{3}$$

$$\begin{aligned} M_{x_B} &= I_{x_1}\dot{p}_1 + I_{x_2}\dot{p}_2 \\ M_{y_B} &= \tilde{I}\dot{q} - (\tilde{I} - I_{x_1})p_1 r + I_{x_2} p_2 r \\ M_{z_B} &= \tilde{I}\dot{r} + (\tilde{I} - I_{x_1})p_1 q - I_{x_2} p_2 r \end{aligned} \tag{4}$$

where

$$\tilde{I} = I_{y_1} + I_{y_2} + m_1 x_1^2 + m_2 x_2^2 \tag{5}$$

For aeroballistic axes: (do not spin with outer body):

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} = (1/m) \begin{bmatrix} F_{x_A} \\ F_{y_A} \\ F_{z_A} \end{bmatrix} + \begin{bmatrix} rv - qw \\ -ru \\ qu \end{bmatrix} \tag{6}$$

$$\begin{aligned} M_{x_A} &= I_{x_1}\dot{p}_1 + I_{x_2}\dot{p}_2 \\ M_{y_A} &= \tilde{I}\dot{q} + (I_{x_1} p_1 + I_{x_2} p_2)r \\ M_{z_A} &= \tilde{I}\dot{r} - (I_{x_1} p_1 + I_{x_2} p_2)q \end{aligned} \tag{7}$$

It can be shown that, for linear aerodynamics, an approximate solution for the angle of attack is

$$\vec{\alpha} = \sum_{j=1}^{2} K_j e^{\phi_j t} \tag{8}$$

where

$$\phi_j = \lambda_j + i\omega_j \tag{9}$$

$$\omega_{1,2} = (p_1 I_{x_1} + p_2 I_{x_2})(1 \pm 1/\tau) / 2\tilde{I} \tag{10}$$

$$\tau = 1 / \sqrt{1 - 1/s} \tag{11}$$

$$s = (p_1 I_{x_1} + p_2 I_{x_2})^2 / 4\tilde{I} M_\alpha \tag{12}$$

$$\begin{aligned} \lambda_{1,2} = {} & Z_\alpha (1 \mp \tau) / 2mv + (M_q + M_{\dot{\alpha}})(1 \pm \tau) / 2\tilde{I} \\ & \pm M_{p_\alpha} p_1 \tau / (p_1 I_{x_1} + p_2 I_{x_2}) \end{aligned} \tag{13}$$

The necessary and sufficient conditions for stability are:

$$\begin{matrix} s > 1, \\ \text{OR} \\ s < 0 \end{matrix} \qquad \lambda_{1,2} < 0 \tag{14}$$

The maximum angle of attack due to an angular rate now becomes:

$$|\vec{\alpha}_{MAX}| = 2\,|\dot{\vec{\alpha}}_0| \Big/ \sqrt{(p_1 I_{x_1} + p_2 I_{x_2})^2 / \tilde{I}^2 \cdot 4M_\alpha / \tilde{I}} \tag{15}$$

Consequently, the maximum angle of attack due to an angular rate is reduced by increasing the angular momentum of either the inner or outer bodies and the stability of the store depends on equations (13), (14), and (15).

III. DISCUSSION

The fly wheel complicates the design of an external store. However, folding fins, parachutes, etc. also complicate the design and are not always effective in improving its overall performance. The overall performance of a store would be improved according to equations (12) through (15) if a properly designed fly wheel were inserted.

The fly wheel concept might be employed successfully to reduce the launch disturbance of low density stores, which have always been troublesome, or of high density stores at supersonic speeds. It could also be used to improve the stability of marginally stable stores or to gyroscopically stabilize stores which are statically unstable.

IV. NOMENCLATURE

$F_{x_A}, F_{y_A}, F_{z_A}$	Forces along the X_A, Y_A, Z_A axes.
$F_{x_B}, F_{y_B}, F_{z_B}$	Forces along the X_B, Y_B, Z_B axes.
I_x, I_y	Rolling and pitching moments of inertia.
I_{x_1}, I_{x_2}	Rolling moment of inertia of outer body and inner body.
I_{y_1}, I_{y_2}	Pitching moment of inertia of outer body and inner body.
K_1, K_2	Complex constants defined by the initial conditions.
m	Total configuration mass.
m_1, m_2	Masses of outer and inner bodies.
$M_{p\alpha}$	Magnus moment stability derivative.
$M_q + M_{\dot{\alpha}}$	Pitch damping moment stability derivative.
$M_{x_A}, M_{y_A}, M_{z_A}$	Moments about the X_A, Y_A, Z_A axes.
$M_{x_B}, M_{y_B}, M_{z_B}$	Moments about the X_B, Y_B, Z_B axes.
M_α	Pitching moment stability derivative.
p, q, r	Angular velocity components resolved along the X, Y, Z axes.
s	Gyroscopic stability factor.
t	Time
$\dot{u}, \dot{v}, \dot{w}$	Body linear velocity components resolved along the X, Y, Z axes.
X,Y,Z	Right handed co-ordinate system when X is the missile axis of symmetry.
x_1	Distance from center of gravity of outer body to total configuration center of gravity.

x_2	Distance from center of gravity of inner body to total configuration center of gravity.
Z_α	Normal force stability derivative.
α	Complex angle of attack.
$\lambda_{1,2}$	Dynamic damping factors.
ω_1, ω_2	Nutation and precession frequencies.

SUBSCRIPTS

$(\,)_A$	Aeroballistic axis system.
$(\,)_B$	Body fixed axis system.
$(\,)_1$	Outer body.
$(\,)_2$	Inner body.

V. REFERENCES

1. Frick, C. H., *"Equations of Motion for Two Rigid Bodies Coupled by a Bearing,"* Naval Proving Ground Report 1630, 25 November 1958.